Fast-Response Engine Research
Years 1 and 2 Overview

Propulsion Controls & Diagnostics Workshop
Cleveland OH
December 8 - 10, 2009

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Acknowledgements

NASA: Dr. OA Guo and Jonathan Litt

Scientific Monitoring Inc: Dr. Walt Merrill

University of Connecticut: Prof Chengyu Cao
Andrew Thompson

Pratt & Whitney: Dr. Jim Fuller (Controls Fellow)
Nicole Romeo (Program Office)

Agenda

Why Fast-Response Engine Research?

Project Goals, Objectives and Plan

Three-Phase Approach

- Phase 1: Requirements Definition
- Phase 2: Control Law Development
- Phase 3: Verification and Validation

Summary

NASA Aviation Safety Technical Conference
Denver, CO, Oct 22 - 24, 2008

NASA Aviation Safety Technical Conference
Mclean, VA, Nov 17 - 19, 2009

This Presentation Derived from Charts Presented at Two Av Safety Conferences

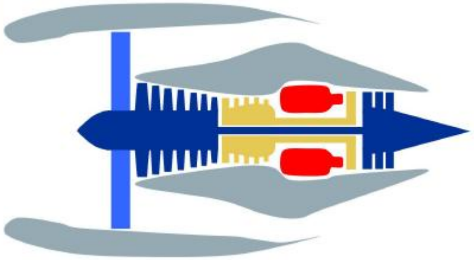
Motivation

Why Fast-response Engine Research?

Loss of Control

United Flight 232 in Sioux City, IA
July 1989

American Flight 587 in Queens, NY
November 2001



What Can The Engines Do To Help?

Runway Incursion

USAir 1493 / SkyWest 5569 at LAX
February 1991

Comair Flight 5191 in Lexington, KY
August 2007

Project Goal and Objectives

Aviation Safety Program *Integrated Resilient Aircraft Control*

Fast-response Engine Research (FastER)

"Arrive at a set of validated multidisciplinary integrated engine control design tools and techniques for enabling safe flight in the presence of adverse aircraft conditions…"

- Improve Flight *Safety* and *Survivability* of Aircraft Under Abnormal or Emergency Conditions Such As Faults, Damage or Upsets
- Investigate and Design a Notional Fast-response Engine Controller:
  - Boost (Or Recover) Engine Capability by Relaxing Normal Physical and Operational Limits During an Emergency Until Aircraft Lands Safely
  - Enhanced Engine Capability Is Primarily *Increased and Faster Thrust*; Produced By Balancing Against Maintaining Operating Margins and Remaining Life Of Critical Engine Components

Engine Challenges:
- Response Typically Slow as Compared to Aircraft Control Surfaces
- Thrust Levels Typically Limited to Meet "Full-Life" Operation Specs

Ground Rules

Leading to Fast-response Engine Controller Design

Target Application:

- Generic High-Bypass Turbofan Engine for Commercial Transport Aircraft

For Research:

- Select and Focus On Just Two Specific Representative Scenarios
- Study Impact of Over-Thrust Operation on Engine Component Life
- Evaluate Impact of Fast Response on Engine Transient Stability
- Determine Means of Selectively Extending Engine Operation Limits
- Research Use of Traditional and Unconventional Control Modes
- Facilitate Development of New Strategies/Concepts By Other Researchers

Assume:

- No Damage to the Engine, But Do Consider Normal Degradation
- *Adverse Condition Indicator* Provided to Engine Controller
- Aircraft Scenarios Start from a Stabilized Condition – Don't Worry About Recovery

Develop and Demonstrate a *Notional* Controller That Provides Increased and Faster Thrust During Emergency Operations

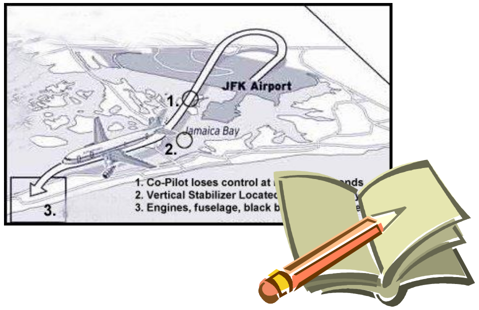
Three Phase Program Structure

Aviation Safety Program | **Integrated Resilient Aircraft Control**

Working in a Simulation Environment

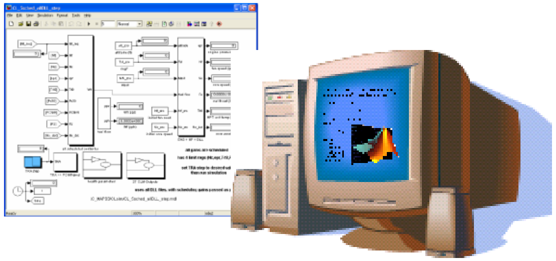
Requirements

- **Scenario Simulations**
- **Requirements Definition**



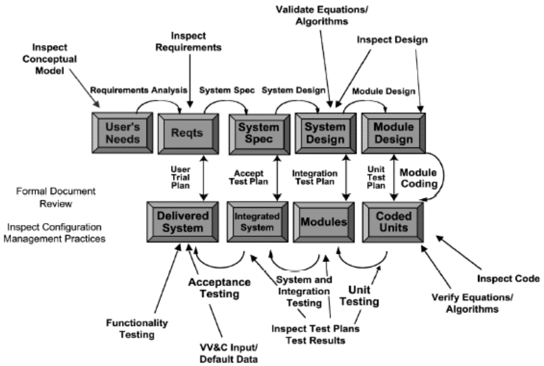
Control Law Development

- **Theories & Methods**
- **Available Engine Capabilities**
- **Simulation Evaluations**
- **Risk Trade-offs**



Verification/Validation

- **V&V Plan**
- **Certification Barriers Identification**
- **Simulation Evaluations**



Requirements Definition

Aviation Safety Program | **Integrated Resilient Aircraft Control**

Requirements for Control System Modifications

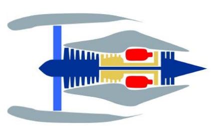
Select Scenarios

Loss of Control:
Rudder / Tail Failure

Takeoff
Runway Incursion

Simulate Scenarios

Engine Model w/ "Relaxed" Limits



Minimum Response

Minimum Additional Thrust

Limits

- Low Rotor Max Speed
- High Rotor Max Speed
- High Rotor Speed Rate
- Max/Min Burner Pressure
- Max Turbine Temperature
- Actuator Limits
- *etc.*

Hardware Considerations

Operability

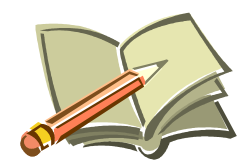
Structural

Response

Additional Thrust

"Tradable" Limits

Control System Requirements

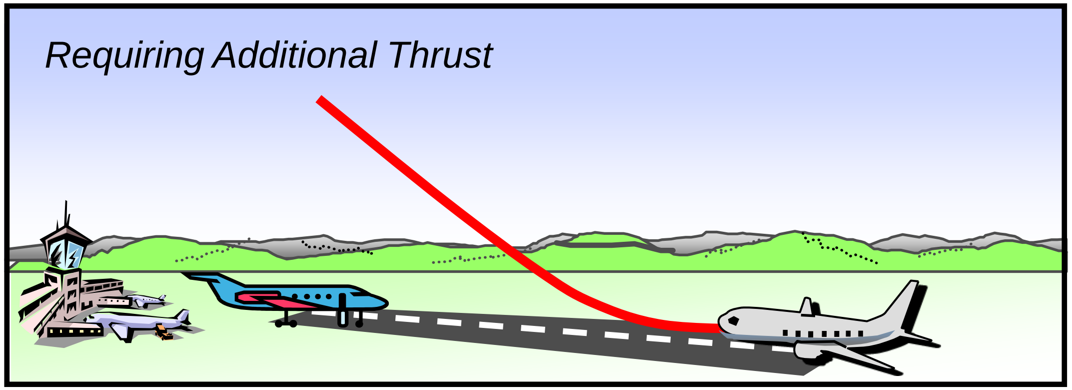


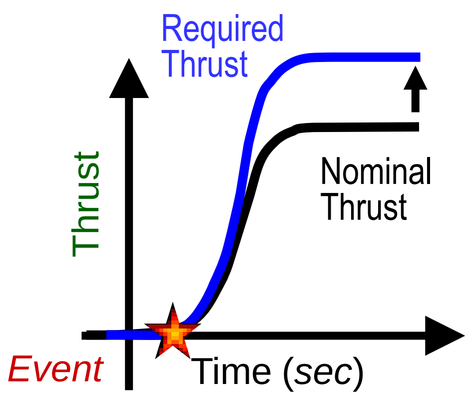
Emergency Goals and Constraints

Requirements Definition

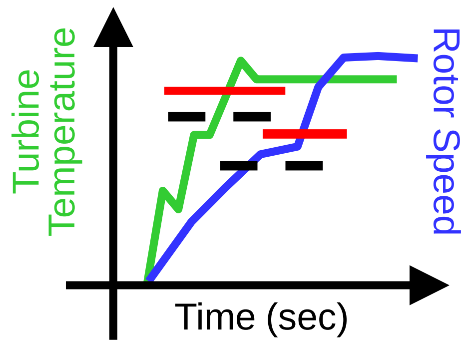
Aviation Safety Program **Integrated Resilient Aircraft Control**

Scenario ❶ Takeoff Runway Incursion





Max Temp/Speed Limits



Adverse Condition

Plane Crossing Runway During Takeoff Roll

Operating Conditions

Start Condition: SLS

Throttle Setting: Take-Off – Begin Roll

Event Initiation

Aircraft-Crossing Runway During Roll

Pilot Action

Snap Full Throttle – Hard Pull Up

Repeat with "Bent Throttle" Capability

Derived Engine Requirements

- Increased Maximum Thrust
- Short Duration (< Minute)
- Ensure Engine Does Not Fail

Scenario

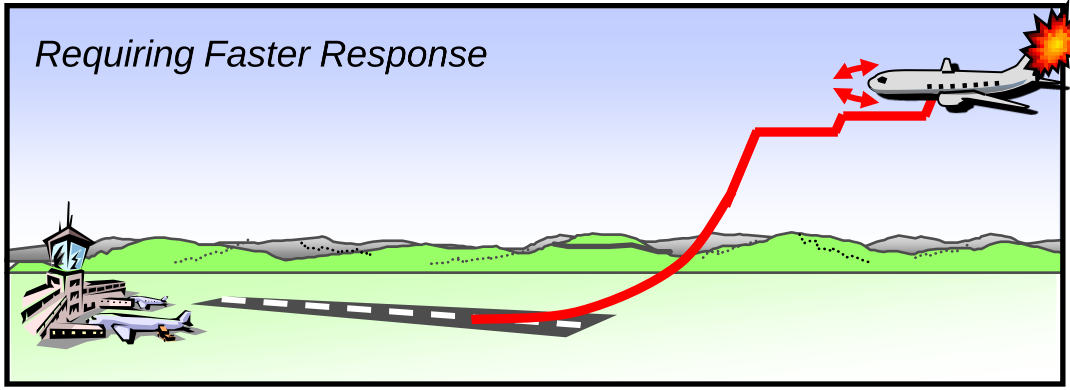
Durability Analysis for Increased Thrust

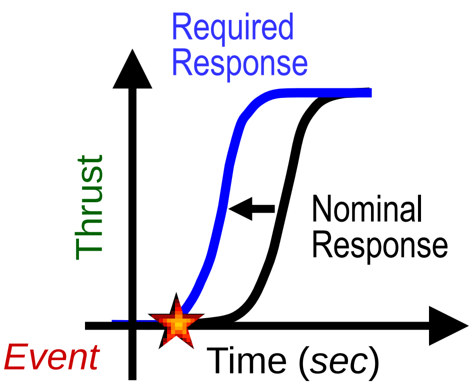
Real-Time Trading of Part Life for Thrust

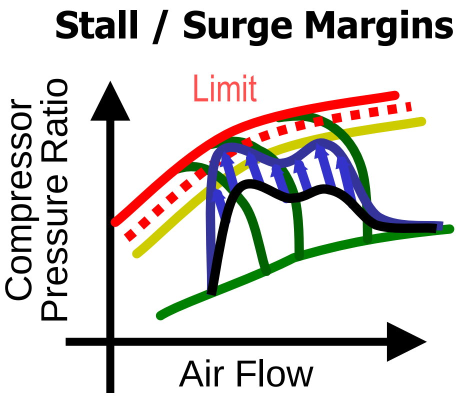
Requirements Definition

Aviation Safety Program — **Integrated Resilient Aircraft Control**

Scenario ❷ Loss of Control: Rudder / Tail Failure







Adverse Condition

Sudden Loss of Rudder Control

Operating Conditions

Flight Conditions: 4500 feet / 250 kts

Throttle Setting: Flight Idle / 6500 lbf Thrust

Event Initiation

Abrupt Loss of Rudder Function

Start from Stabilized Condition

Initiate Turn Requiring Rudder Function

Pilot Action

Asymmetric Engine Thrust Modulation

Derived Engine Requirements

- Decrease Accel / Decel Times
- Maintain Adequate Margins / No Stall

Scenario

Operability Analysis for Fast Response

Real-Time Stability Audit

Aircraft Simulator Research

Boeing Conducted Workstation (Non-Piloted) Simulator Study Using Generic Large Multi-Engine Transport Aircraft

- Full-Up Aircraft Model
- Nonlinear Engine Aerodynamic Model for Thrust Levels
- Simple Engine Transient Model (1st Order Lag w/ Position & Rate Limits)
- Adjusted Engine Model Parameters to Determine Engine Requirements
- Throttle Inputs Predetermined via “Script” … Autopilot Also Used

Two Specific Scenarios Developed

1. Runway Incursion Presents 1000 Ft (25 Sec) Into Takeoff Roll
2. Rudder Failure On Approach To Airport

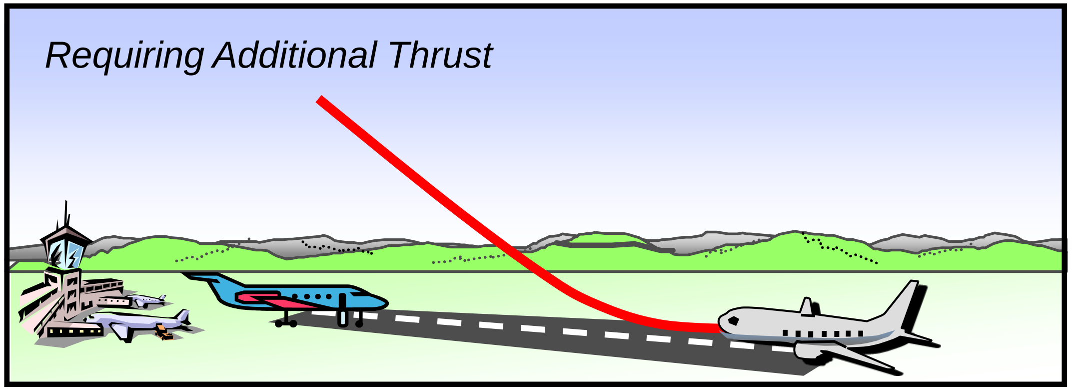
Prior NASA Throttle Controlled Aircraft (TCA) & Propulsion Control Aircraft (PCA) Studies Also Provided Requirements

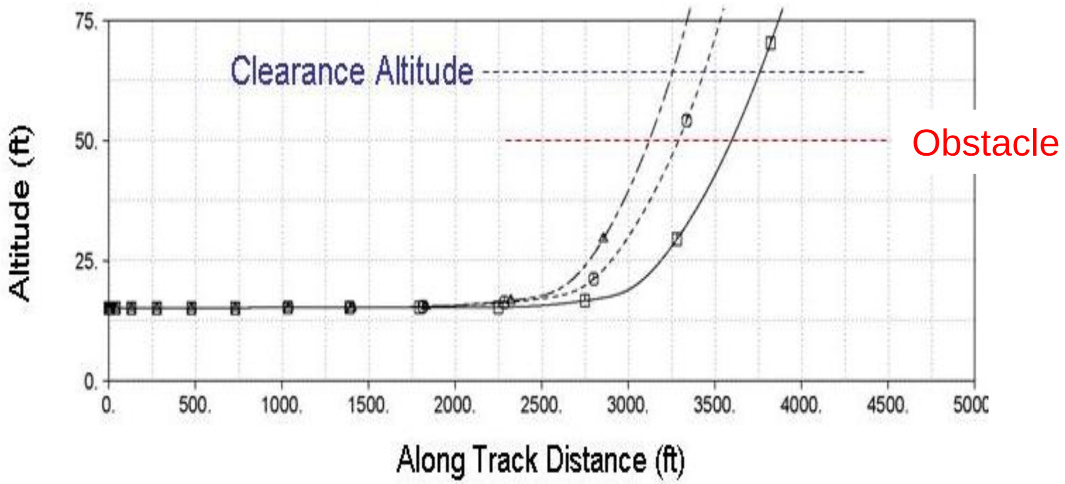
- At Approach Thrust Levels, Nominal Engine Response Was Found Too Slow For Pilot To Use To Effectively Dampen Aircraft Dynamic Modes

Requirements Definition

Aviation Safety Program | **Integrated Resilient Aircraft Control**

Scenario ❶ Takeoff Runway Incursion – *Simulator Results*





Adverse Condition

Plane Crossing Runway During Takeoff Roll

Operating Conditions

Start Condition: SLS

Throttle Setting: Take-Off – Begin Roll

Pilot Action

Snap Full Throttle – Hard Pull Up

Derived Engine Requirements

- Increased Maximum Thrust
- Short Duration (< Minute)
- Ensure Engine Does Not Fail

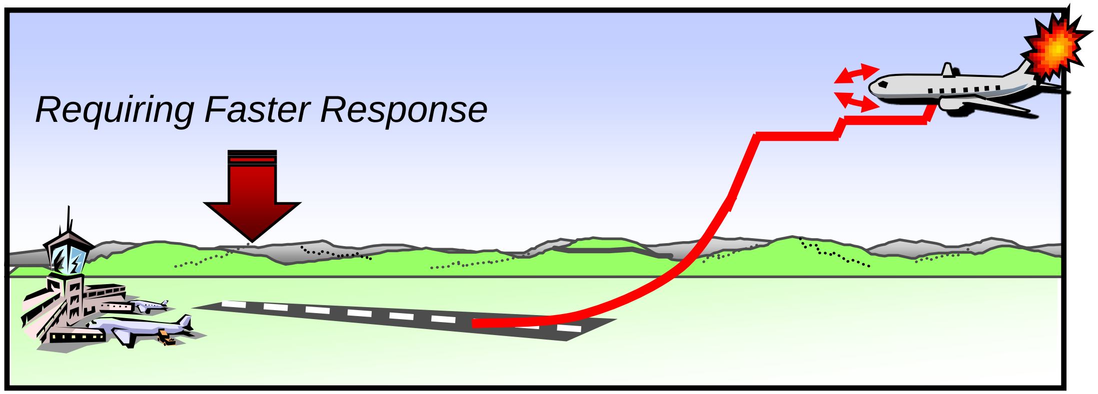
Scenario

10% Emergency Overthrust Capability Decreases Distance Needed to Clear Obstacle by 270 ft; 20% Decreases Distance by 450 ft.

Requirements Definition

Aviation Safety Program **Integrated Resilient Aircraft Control**

Scenario ❷ Loss of Control – Rudder Failure – *Simulator Results*



Adverse Condition

Sudden Loss of Rudder Control

Operating Conditions

Flight Conditions: 4500 feet / 0.25 Mach

Throttle Setting: Flight Idle / 6500 lbf Thrust

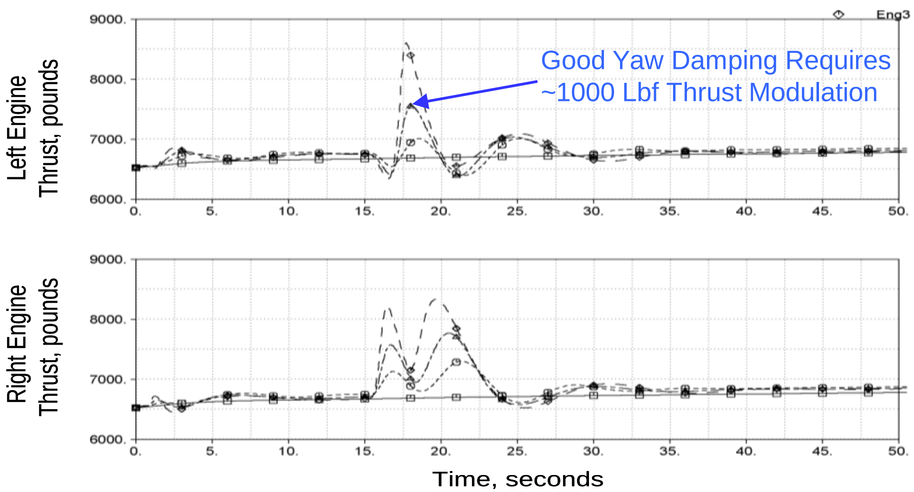
Pilot Action

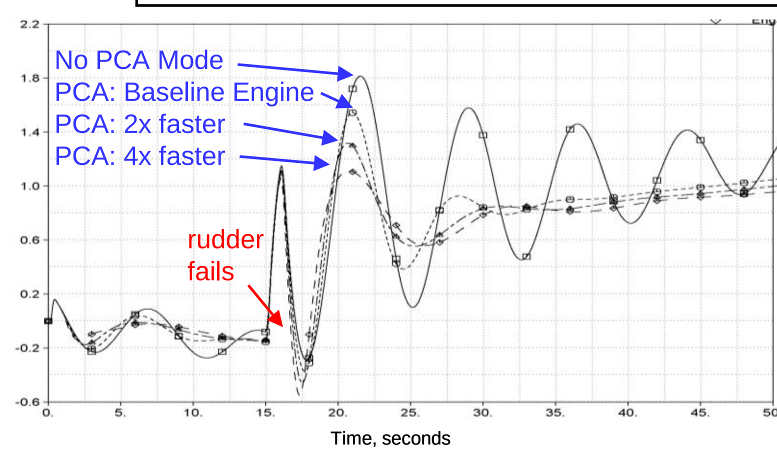
Asymmetric Engine Thrust Modulation

Derived Engine Requirements

- increase Responsiveness

Scenario





2x Faster Engine Response Significantly Improves Yaw Damping In A Propulsion Controlled Aircraft (PCA) Mode

Phase 2: Control Law Development

Establish a Baseline Engine Control System

Flow Down Aircraft / Engine Requirements Into Control Requirements

Identify Engine Control System Actuation Options

- Evaluate Existing Actuation Options (P&W)
- Consider Both Existing and New Actuation Approaches (SMI)
- Rank Actuation Options Based on Effectiveness and Impact

Develop Engine Control Modes for Emergency Maneuvers

Design Control Laws for High Potential Emergency Control Modes

- Consider Both Classical and Modern Design Methods
- Take Into Account Time-Varying / Event-Driven Constraints
- Incorporate Risk Evaluation in Design

Evaluate Designs Through Simulation

Engine Simulation Supporting Controls

Using NASA's New C-MAPSS40K

- Simulation-Based Study As To How To Provide Required Engine Response by Modification of Engine Control Laws
  - Used NASA C-MAPSS40K Simulation of Generic Transport Engine
  - Features Detailed Transient Aero-Thermal Model
  - Includes Base Control Laws
  - Control Laws Can Be Modified To Design & Validate New Control Laws
- Created New Emergency Adaptive Control Law as Perturbation to Baseline Engine Control
  - Modifies Commands To Baseline Engine Controller
- Used to Show Ability to Trade-Off of Engine Life, Efficiency, and Margins for Increased Responsiveness and Additional Thrust

Design Trade-Off: Performance & Limits

Improve Performance

Increase Speed
Increase Magnitude

Risk

Exceed Temp Limits → Engine Life Expectancy
Exceed Fan/Core Speed

Exceed Stall/Surge Margin → Engine Stalls

Trade-Off

Improved Performance While Maintaining Output Limits

Adaptive Controller with Output Limits

L1 Adaptive Control

- Novel Control Approach Using Fast & Robust Adaptation
- No Tuning Process Involved
- Guaranteed Transient Response
- Guaranteed Stability Margin (Time-Delay Margin)
- Handles Nonlinear Time-Varying Uncertainties

- Extension via IRAC: L1 Adaptive Control w/ **Output Limits**

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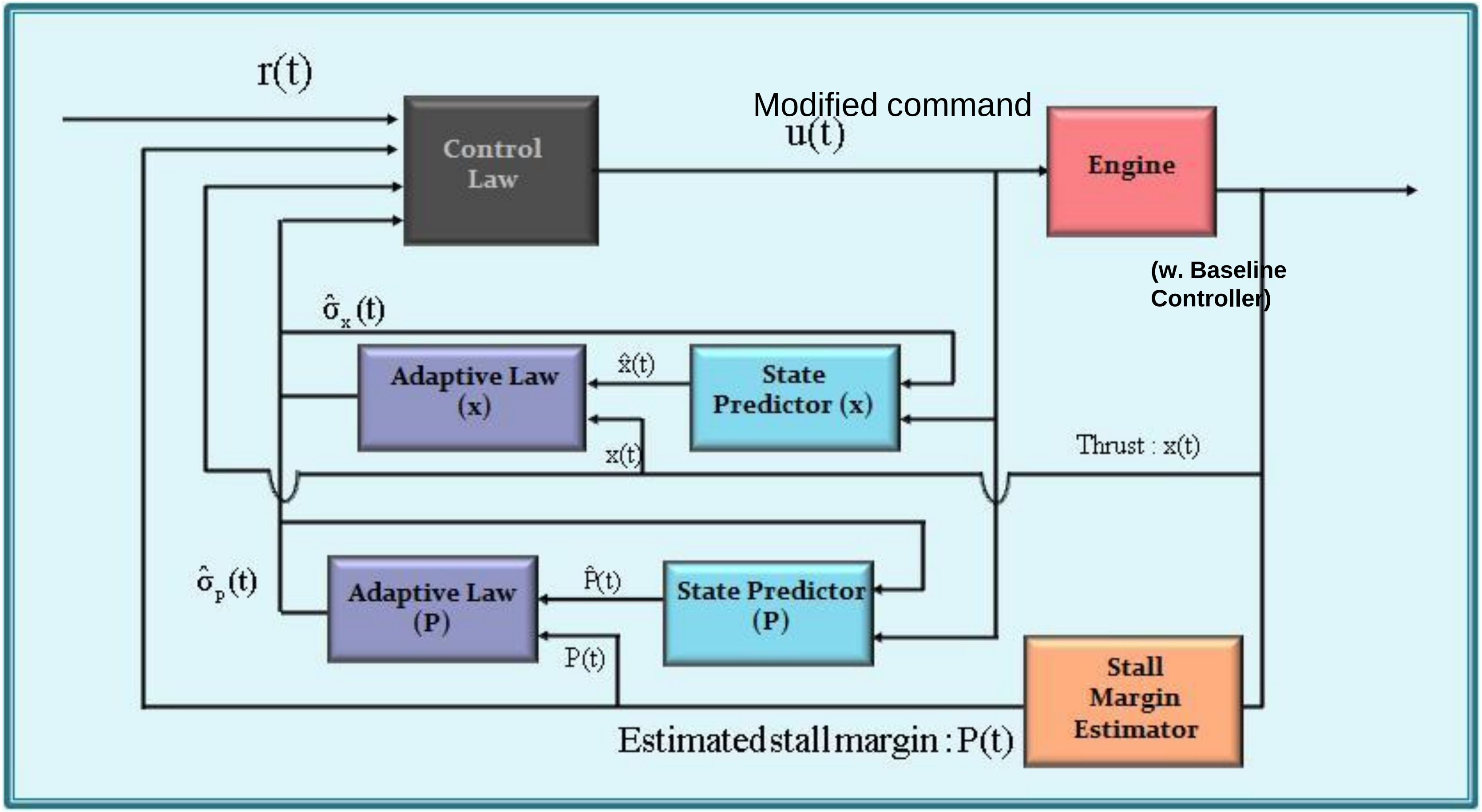
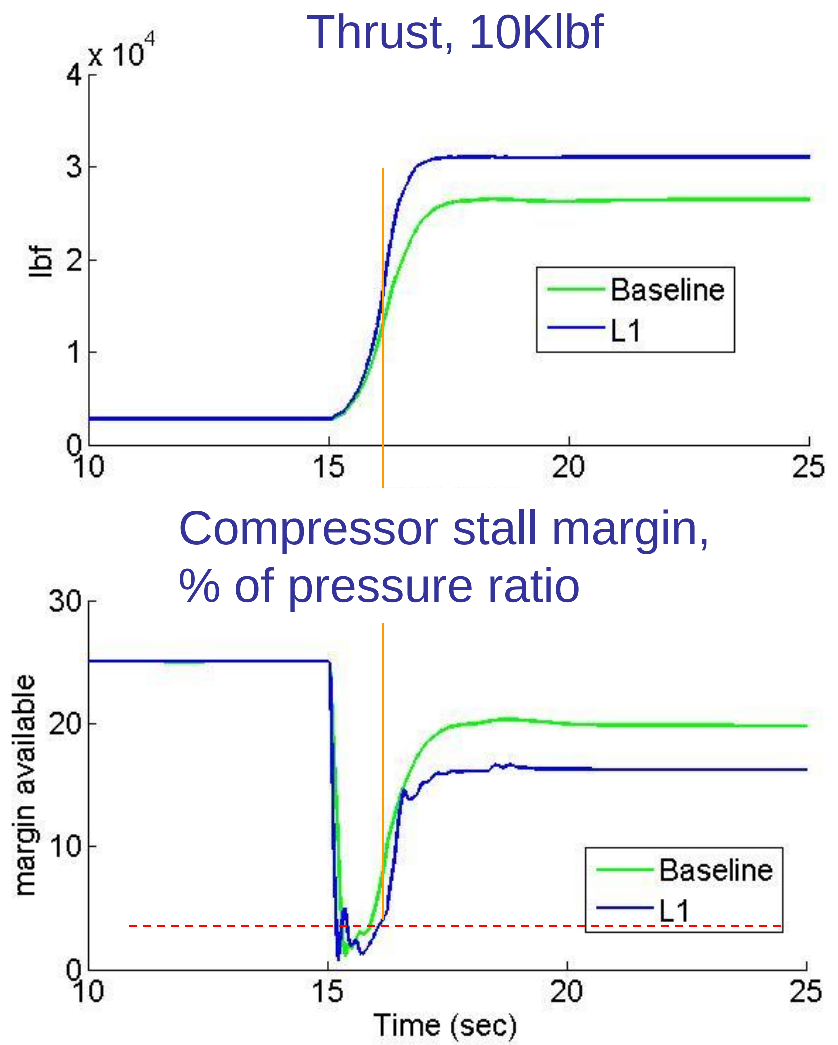
L1 Adaptive Architecture



10% Overthrust Results

Aviation Safety Program — **Integrated Resilient Aircraft Control**

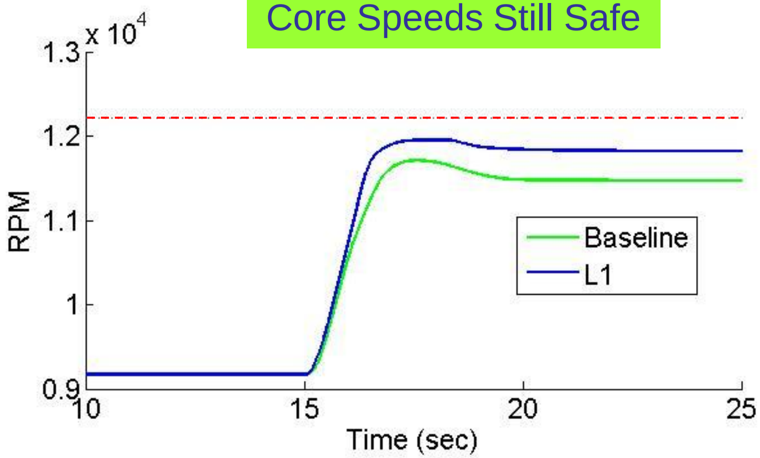
- Take-Off Conditions
  - Alt = 1500 ft, MN=0.3, Standard Day
- Idle to 100% or 110%
- Two Controllers
  - Baseline (100%)
  - L1 adaptive (110%)
- Both Responses Initially Limited to Hold High Compressor Stall Margins
  - key limit on large accels
  - 0% margin is acceptable



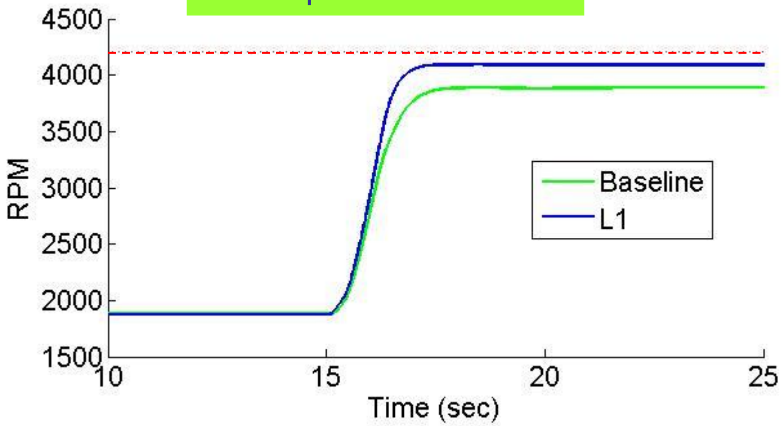
10% Overthrust: Other Safety Critical Parameters

Aviation Safety Program ***Integrated Resilient Aircraft Control***

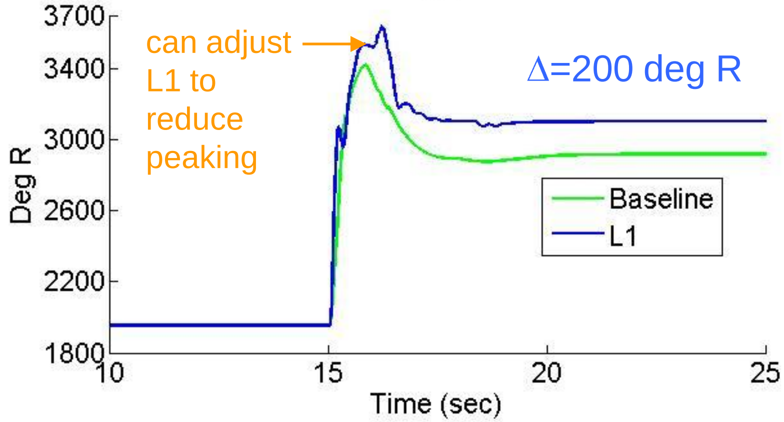
Core Speeds Still Safe



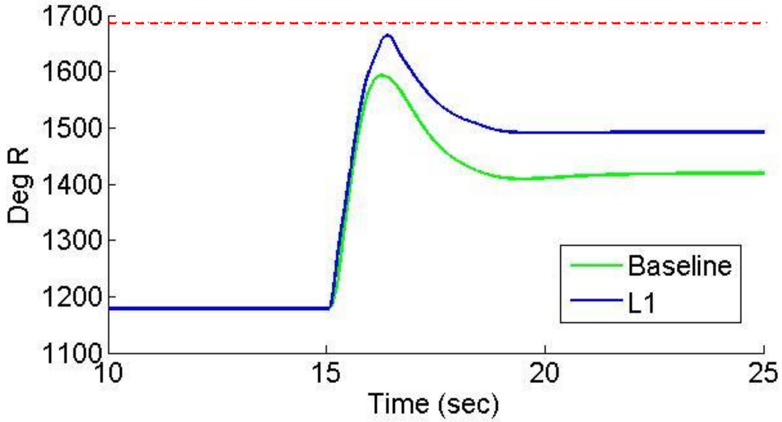
Fan Speeds Still Safe



Increased Turbine Inlet Temp => Life Usage



Turbine Exit Temp A Maintenance Parameter

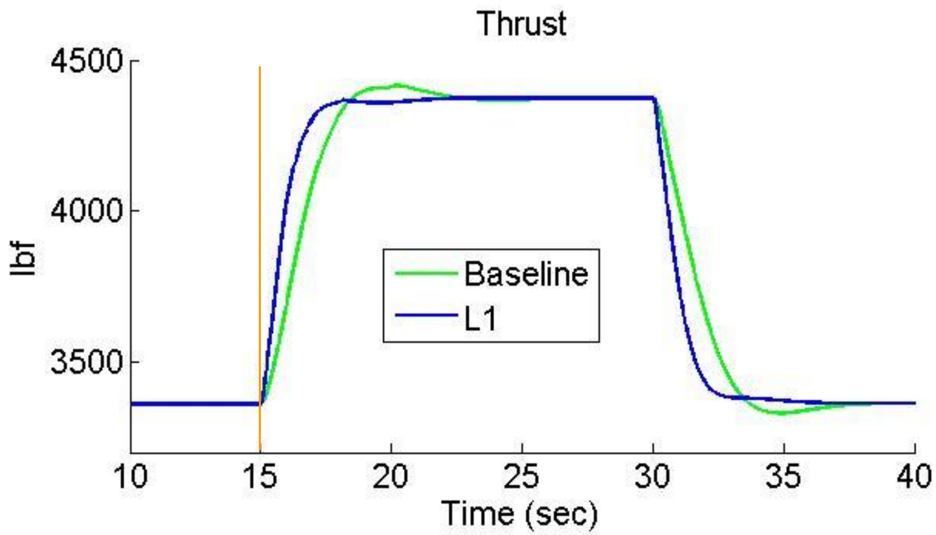


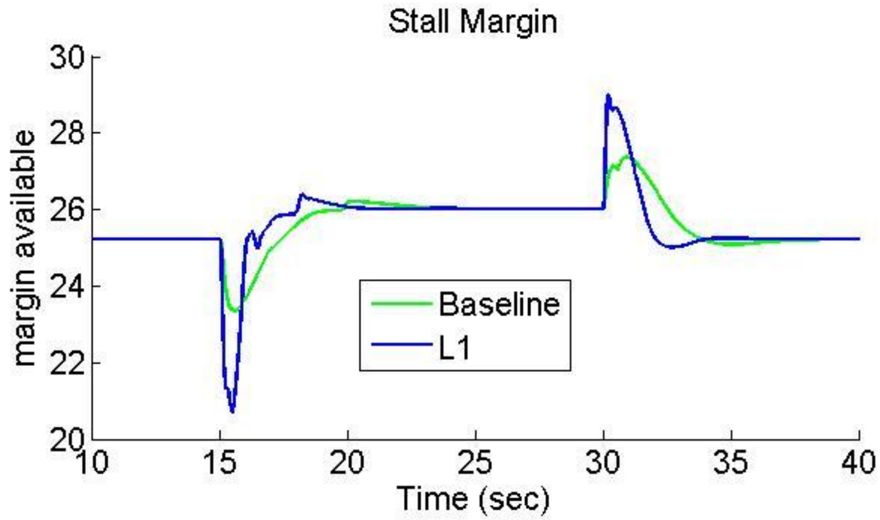
10% Overthrust Reduces Remaining Life, But Is Otherwise Safe

Arresting Yaw Transient: 1000 Lbf Step

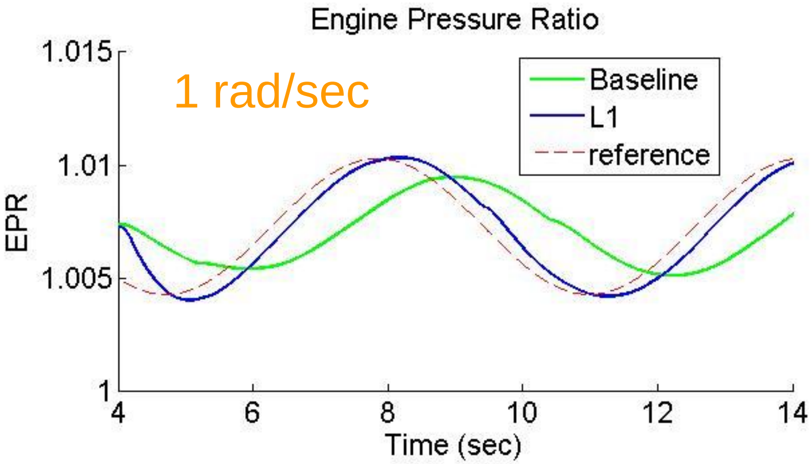
Aviation Safety Program *Integrated Resilient Aircraft Control*

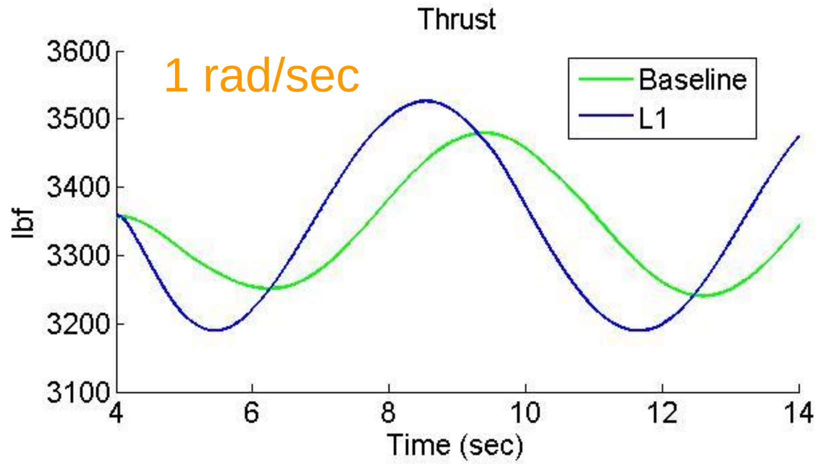
- Approach Conditions
  - Alt=1500 ft, MN=0.3,
  - Standard Day
  - 4300 Lbf Approach Thrust
- Rudder Failure Scenario
  - Initial 1,000 Lbf Transient Needed To Arrest Yaw Transient
- L1 Adaptive Control logic Cuts Response Time 50%
- Safety and Stability Limits Not a Factor

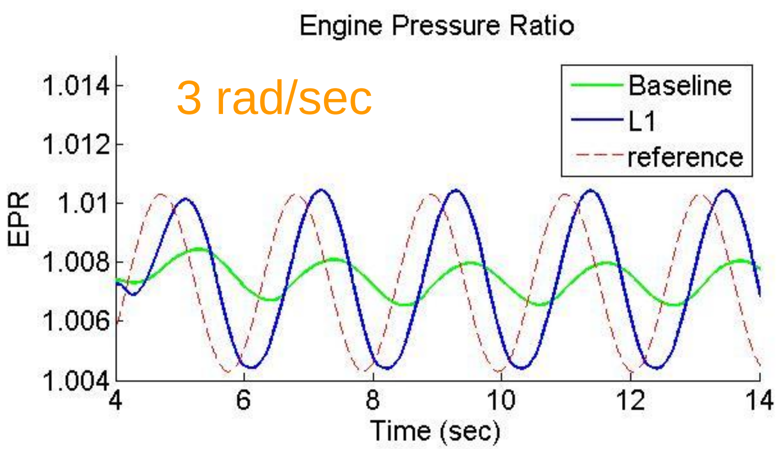


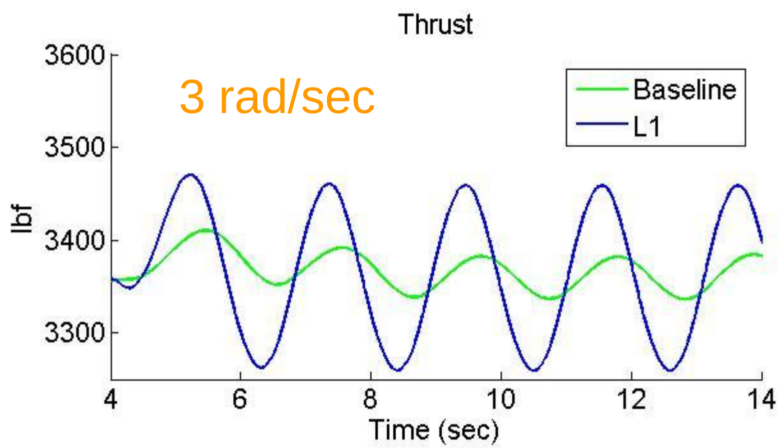


Increase Bandwidth to Support PCA Damping









L1 Control Triples Command Response Bandwidth

Plan for Further Control Law Efforts

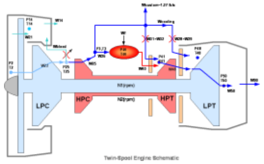
- Continue to Evolve L1 Adaptive Control Theory
  - Extend To Dealing w/ Multiple Output Limits
  - Look at Alternate Adaptive Augmentation Architectures
- Generate Estimates of Degradation & Life Usage
- Investigate More Aggressive Use Of:
  - Bleeds
  - Inlet Guide Vanes
- Develop Validation Requirements and Plans

Phase 3: Verification and Validation

Aviation Safety Program *Integrated Resilient Aircraft Control*

Addressing Both Verification/Validation and Certification

C-MAPSS40K +
Fast Response
Control Laws



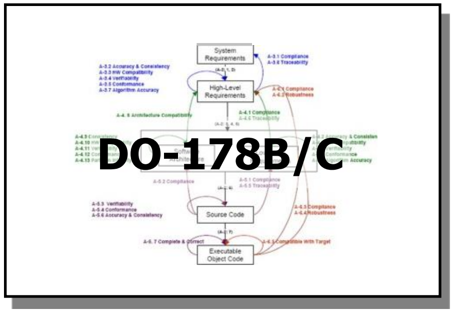
Updated Simulator

Re-Fly Scenarios w/ New Control

Simulator Testing

Test Plan

Certification Considerations



- *Identify Potential Certification Challenges*
- *Recommended Approaches to Certification*

Summary

- Propulsion Systems Can Be Used To Improve Aircraft Safety
  - But They Need The Ability to Exceed Nominal Control Limits for Emergency Situations … *While Continuing to Operate Safely Themselves*
- **FastER** is Three-Phase Program to Develop Means to Do This
  - Phase 1 - Requirements Development
  - Phase 2 – Control Development
  - Phase 3 – Verification and Validation Considerations
- **FastER** Preliminary Results Indicate Benefits of Small Adaptation
  - Multiple Representative *Requirements Definition* Scenarios Selected
  - Control Requirements Derived From Simulator Testing
  - Emergency Control Modes Selected and Implemented
  - Initial Control Mode Simulation Results Very Encouraging
- Next Steps
  - Mature Control Designs
  - Begin To Address Validation